SF 298 MASTER COPY KEEP THIS COPY FOR REPRODUCTION PURPOSES

REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	30 Sept 95	Final 15 May 92 to 30 Sept 95

4. TITLE AND SUBTITLE
Investigation of Optical Processing, Holography and Interferometry with Femtosecond Pulses

5. FUNDING NUMBERS
DAAL03-92-G-0230

6. AUTHOR(S)
Emmett N. Leith

7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(ES)
University of Michigan
Dept of Electrical Engineering and Computer Science
Ann Arbor, MI 48109-2122

8. PERFORMING ORGANIZATION REPORT NUMBER
DRDA 91-2935
DRDA 92-0127

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING / MONITORING AGENCY REPORT NUMBER
ARO 29339.28-PH

11. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12 b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
A variety of methods were developed for imaging through highly scattering material, such as biological tissue. The aim is to be able to see objects hidden within the material. The techniques use advanced electronic cameras that are cooled to very low temperature, as well as considerable computer processing. Experimental results show these methods to be highly effective. In addition, we developed new techniques in confocal imaging, including a method for enhancing the depth-discrimination capabilities of the process. Finally, we extended a technique we developed earlier: the transmission of three dimensional images through, single, single-mode optical fibers using monochromatic light. The imaging process works on the basis of optical coherence, hence the process is called coherence imaging.

19960523 036

14. SUBJECT TERMS
electronic holography, first-arriving light, image processing

15. NUMBER IF PAGES
8

16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

Investigation of Optical Processing, Holography and Interferometry with Femtosecond Pulses

Final Report

Emmett N. Leith
9/30/95

submitted to:
U. S. Army Research Office

Grant No. DAAL03-92-G-0230
Grant No. DAAL03-92-G-0200

submitted by:
Department of Electrical Engineering and Computer Science
University of Michigan
Ann Arbor, MI 48109-2122

A. Statement of Problem Studied

The aim of the grant was severalfold: to investigate electronic holography for imaging through scattering materials, especially biological tissue, to explore 3-dimensional information acquisition with short pulse light and to investigate the transmission of 3-dimensional uses in optic fibers using coherence techniques.

B. Summary of the most important results

Our principle results during this grant have been the following: (The reference numbers after the statements refer to the paper in which the work was published).

1. We ran a test program to evaluate different methods for imaging through biological tissue, using chicken breast. We developed a multiparameter graph for evaluation purposes, in which resolution is plotted as a function of specimen thickness. Theoretical resolution is plotted on the graph for a range of source coherence lengths. A second set of curves, giving compression ratios (the ratio of the point spread function width using standard transillumination to the point spread function width achieved with our processing methods). When experimental data is plotted on this graph it becomes possible to ascertain how closely we are achieving the theoretical resolution and also to ascertain how the parameters should be altered to improve the imaging.

In the process, we developed a simplified, quite useful theory for computing the expected resolution through an arbitrary thickness of highly scattering material, assuming no more than that the material is essentially a Lambertian scatterer. An extensive experimental program verified the correctness of the theory. (refs. 3,5)

2. We improved our first-arriving light imaging system by replacing the old mechanical scanning system for scanning the dye laser throughout a prescribed wavelength range with an electronic modulator that can do the scanning at kilohertz rates, that can be put under computer control, and that can give an arbitrary, computer-controlled nonlinearity to the scan so as to arbitrarily shape the spectrum of the dye laser, thus shaping the autocorrelation function. In this way, we hope to obtain an autocorrelation function with extremely low sidelobes, which should enhance the capability for achieving high signal to noise ratio.

3. We developed a new kind of holography, which we call mutual coherence holography. This is a kind of image-plane holography, in which the holographic image is always formed in the plane of the recording medium, even though in the hologram formation process, it is unnecessary to image the object distribution onto the hologram. (ref. 4)

4. We used electronic holography to image through living human tissue. Specifically, we imaged a pair of crossed wires through the flesh of a living human hand. The principle significance of the work is that this was accomplished without the use of short pulse high peak intensity laser sources such as are typically used for imaging of human subjects, such as portrait holography, but with a cw low power laser, in which the light level reaching the object surface was only a few mw. What made such holographic imaging possible is the high sensitivity of the CCD camera and its capability for making multiple holograms in rapid succession, thus improving the signal to noise ratio. (ref. 12)

5. A confocal imaging system based on broad source electronic holography was developed. Such a system achieves confocal-type imaging without the need for the double scanning process typically required for confocal systems. The system has been demonstrated as a method for optical sectioning, i.e., it can focus on a narrow range within a 3-D object and reject the light from other depth sections of the object. (ref. 9)

6. We developed a spectral dispersion imaging system for imaging through scattering media. In this system, the first arriving light principle is combined with that of spectral holography. A diffraction grating is incorporated into the system downstream from the object, so that both the object and reference beam are dispersed into their spectral components. In so doing, each portion of the resulting hologram is formed with narrow-band light, giving fringes with high contrast, and ultimately, an image with high signal to noise ratio. This system is a solution to one of the major problems of the holographic method for imaging through scattering media: ambient background produced by the portion of the light that does not interfere with the reference beam is detrimental, leading to low fringe contrast. Now, all of the light interferes with the reference beam, and the fringe contrast is high. (ref. 7)

7. We developed a new idea for detection of non-stationary objects: The speckle differencing method. We expect that its greatest effectiveness will be when it is combined with some of the other techniques we have employed. The method depends upon the motion of objects. We suppose that some objects embedded in a scattering medium have motion. The light that has passed through the scattering medium broadly falls into two categories: Light that has not been scattered by both the stationary scatterers and at least one moving scatterer, and light that has been scattered by a moving scatterer.

The former produces a time invariant speckle pattern, and the latter a time variant speckle. Two successive speckle patterns are recorded by the CCD camera and subtracted. The process at once removes all of the light that is of no interest. This process gives improved SNR, but no improvement in resolution; its combination with some of the resolution improvement processes appears to offer a powerful capability for imaging into scattering media. (ref. 19)

8. We carried out a project on time lens imaging. The time lens was invented in the 1960's, but has seen a revival of interest resulting from the development of ultrafast optics. We advanced the theory of time lenses in several ways, the most significant being the development of a time lens analog of spatially incoherent imaging processes. The time lens has a number of potential applications; in particular, it can aid in the process of imaging through scattering media; specifically, it has the possibility of time scaling a femtosecond-regime pulse into a much longer, picosecond-regime pulse, which makes detection of the 1st arriving light easier. (ref. 17)

9. We returned to a project we had developed earlier. The use of coherence imaging for forming complete 3-D images through a single optical fiber. We carried the theory further, and we were able to obtain some rather interesting experimental results, showing resolution in the depth dimension. (ref. 22)

10. Noise analysis. The ability to image through highly scattering media such as biological tissue is inherently a noisy process, and there are a variety of noise sources: speckle noise from the scattering nature of the medium, photon noise from the rather high background, "tail" noise, resulting from the lobes or tails of the auto correlation function of the illuminating source light, and several other noise sources. An in-depth analysis was made of all of these noise sources, their effect on the detection of embedded objects and means for overcoming the effects of these noise sources. This work will be published in a recently accepted paper. (ref. 26)

11. Depth discrimination improvement in transmission confocal microscopy. Confocal imaging is a valuable new imaging tool for microscopists. Its most significant attribute is improved depth discrimination when imaging into thick specimens. The confocal process yields suppression of the images from planes of the object that are not in focus; this discrimination is considerably greater than that offered by conventional microscopy. In addition, if the microscopy is carried out in the reflection mode, as opposed to the transmission mode, the use of broadband light and coherent background offers additional depth discrimination. When the background light is coherent with the image-bearing light, the interference between the two can enhance this image, whereas light from a different depth of the object will have traveled a path of different length and will therefore be incoherent with the backround beam, and the lack of interference will suppress the image

from this part of the object. Hence the temporal coherence properties of broadband light enhance the depth discrimination beyond that afforded by the confocal process.

We discovered a way to extend this temporal coherence enhancement effect to transmission confocal microscopy, despite the lack of significant path differences between the light scattered from objects of different depth. (ref. 25)

12. We explored in considerable depth the Fourier decomposition method of imaging through scattering media, extending it in several ways and obtaining good experimental results. This work resulted in published articles and was the greater part of the doctoral dissertation of Eric Arons. (refs. 2,8,15,23,24)

13. The previously reported method of first arriving light speckle differencing to detect moving objects embedded in highly scattering media was extended to produce what we call fringe differencing (again, in combination with first arriving light). The method in essence involves taking the difference of a complex speckle pattern instead of merely the intensity--a feat made possible by the holographic recording of the phase. A significant improvement in the capability for imaging into scattering media resulted.

14. We conceived a new method of imaging into scattering media, and we are currently developing it, both experimentally and theoretically. The technique, though computation intensive, appears to be one of considerable power. We will be reporting on it at a forthcoming Optical Society meeting in Boston this April.

C. List of all publications and technical reports

1992

1. P.-C. Sun and E.N. Leith, "Superresolution by spatial-temporal encoding methods," Appl. Opt., 31, 4857-4862 (1992).

2. E. Leith, C. Chen, H. Chen, Y. Chen, D. Dilworth, J. Lopez, J. Rudd, P.-C. Sun, J. Valdmanis and G. Vossler, "Imaging through scattering media with holography" J. Opt. Soc. Am. A., 9, 1148-1153 (1992). INVITED PAPER

1993

3. C. Chen, H. Chen, Y. Chen, D. Dilworth, E. Leith, J. Lopez, P.-C. Sun, M. Shih and G. Vossler, "Imaging through biological tissue with holography," Proc SPIE (Midwest, 92)

4. P.-C. Sun, "Mutual-intensity lensless imaging system, " Opt. Lett. 18, 394-396, 1993

5. Y. Chen, H. Chen, D. Dilworth, E. Leith, J. Lopez, M. Shih, P.-C. Sun and G.Vossler, "Evaluation of holographic methods for imaging through biological tissue," Appl. Opt., 32. 4330-4336 (1993).

6. E. Leith, E. Arons, H. Chen, Y. Chen, D. Dilworth, J. Lopez, M. Shih, P.-C. Sun and G. Vossler, "Electronic holography for imaging through tissue," Optics & Phot. News, 19-28 Oct. 1993

7. H. Chen, Y. Chen, D. Dilworth, E. Leith, J. Lopez, M. Shih, P.-C. Sun, E. Arons, R. Draper and K. Clay, "Comparison of various holographic techniques for imaging through biological tissue," Proc. SPIE, Vol 2043, 272-277 (1993).

8. E. Arons, D. Dilworth, M. Shih and P.-C. Sun, "Use of Fourier synthesis holography to image through inhomogeneities," Opt. Lett. 18, 1852-1854 (1993).

1994

9. P.-C. Sun and E.N. Leith, "Broad-source image plane holography as a confocal imaging process," Appl. Opt., 33. 597-602 (1994).

10. E. Arons, H. Chen, K. Clay, D. Dilworth, R. Draper, J. Lopez, E. Leith, M. Shih and P.-C. Sun, "New Holographic methods for improved imagery through scattering media," OSA Proceedings on Advances in Optical Imaging and Photon Migration, R.R. Alfano (ed.) 239-243 (1994).

1994 Cont'd.

11. Y. Chen, "Characterization of the image resolution for the first arriving light method," Appl Opt. 33, 2544-2552 (1994).

12. H. Chen, M. Shih, E. Arons, E. Leith, J. Lopez, D. Dilworth and P.-C. Sun "Electronic holographic imaging through living human tissue," Appl Opt. 33, 3630-3632(1994).

13. M. Shih, E. Arons, H. Chen, D. Dilworth, R. Draper, E. Leith, J. Lopez and P. Nalleau, "The challenge of optical imaging through biological tissue," Proc. SPIE, 2333, 314-320 (1994).

1995

14. P.-C. Sun and E. Aron, "Nonscanning confocal ranging system," Applied Optics 34, 1254-1261 (1995).

15. E. Arons and D. Dilworth, "Analysis of Fourier synthesis holography for imaging through scattering materials," Applied Optics 34, 1841-1847 (1995).

16. E. Leith, "Holography with short pulses and other broad spectrum light," Proc. SPIE (Midwest, 95).

17. P. Naulleau and E. Leith, "Stretch, time lens, and incoherent time imaging, "Appl. Opt., 34, 4119-4128 (1995).

18. M. Shih and E. Leith, "Spatial filtering of first-arriving light,: Appl. Opt., 34, 1310-1313 (1995).

19. P. Naulleau, D. Dilworth, E. Leith and J. Lopez, "Detection of moving objects embedded within scattering media by use of speckle methods," Opt. Lett., 20, 498-500 (1995).

20. E. Leith, E. Arons, H. Chen, D. Dilworth, J. Lopez, P. Naulleau and M. Shih, "Coherent optical processing methods for transillumination imaging of biological tissue," Proc. SPIE (San Diego, 1995).

21. E. Leith, P. Naulleau, M. Shih, E. Arons, D. Dilworth, H. Chen and J. Lopez, "Holographic methods for detection of objects in irregular media," Proc. SPIE (San Diego, 1995).

22. P. Naulleau, C. Chen and E. Leith, "Direct 3-D image transmission through single-mode fibers using monochromatic light," Opt. Lett., 21, 36-38 (1996).

23. E. Arons and D. Dilworth, "Improved imagery through scattering media using Quasi-Fourier synthesis holography," accepted by Applied Optics, Oct. 1995.

24. E. Arons and D. Dilworth, "Lensless Imaging using spatial Fourier synthesis holography," accepted by Applied Optics, Oct. 1995.

25. E. Arons and E. Leith, "A coherence confocal imaging system for enhanced depth discrimination in transmitted light." Accepted by Applied Optics, Oct. 1995.

26. P. Naulleau and D. Dilworth, "Noise analysis for the holographic first-arriving light technique." Submitted to Appl. Opt. 1995.

27. P. Naulleau and D. Dilworth, "Holographic first-arriving light signal-to-noise ratio enhancement by differential holography," Opt. Lett, 20, 2354-2356, 1995.

D. List of all participating scientific personnel

1. Emmett Leith P.I.
2. Marian Shih (PhD in 1995)
3. Eric Arons (PhD in 1995)

E. Report of Inventories

We made patentable inventions, but through publication they have gone into the public domain. One important exception is the electronic holography method for imaging into inhomogeneities. On our previous grant we made a disclosure on this and submitted to our intellectual properties office. A patent was applied for and has been issued.